SINGLE FIBER DUPLEX OPTICAL TRANSPORT

Technical Field of the Invention

The invention pertains to optical fiber transmission systems, and is particularly relevant to optical transport systems employing optical amplifiers. In particular the invention teaches an apparatus and method that allows cost effective co-directional operation of an optical amplifier to support full duplex traffic.

Background of the Invention

A goal of many modern long haul optical transport systems is to provide for the efficient transmission of large volumes of voice traffic and data traffic over trans-continental distances at low costs. Various methods of achieving these goals include time division multiplexing (TDM) and wavelength division multiplexing (WDM). In time division multiplexed systems, data streams comprised of short pulses of light are interleaved in the time domain to achieve high spectral efficiency, high data rate transport. In wavelength division multiplexed systems, data streams comprised of short pulses of light of different carrier frequencies, or equivalently wavelength, are co-propagate in the same fiber to achieve high spectral efficiency, high data rate transport.

The transmission medium of these systems is typically optical fiber. In addition there is a transmitter and a receiver. The transmitter typically includes a semiconductor diode laser, and supporting electronics. The laser may be directly modulated with a data train with an advantage of low cost, and a disadvantage of low reach and capacity performance. An external modulation device may also be used with an advantage of higher performance, and a disadvantage of high cost. After binary modulation, a high bit may be transmitted as an optical signal level with more power than the optical signal level in a low bit. Often, the optical signal level in a low bit is

engineered to be equal to, or approximately equal to zero optical power. In addition to binary modulation, the data can be transmitted with multiple levels, although in current optical transport systems, a two level binary modulation scheme is predominantly employed.

Typical long haul optical transport dense wavelength division multiplexed (DWDM) systems transmit 40 to 80 10 Gbps (gigabit per second) channels across distances of 1000 to 3000 kilometers (km) in a single 35 nanometer (nm) band of optical spectrum. A duplex optical transport system is one in which traffic is both transmitted and received between parties at opposite end of the link. In current DWDM long haul transport systems transmitters, different channels operating at distinct carrier frequencies are multiplexed onto one fiber using a multiplexer. Such multiplexers may be implemented using array waveguide (AWG) technology or thin film technology, or a variety of other technologies. After multiplexing, the optical signals are coupled into the transport fiber for transmission to the receiving end of the link.

At the receiving end of the link, the optical channels are de-multiplexed using a de-multiplexer. Such de-multiplexers may be implemented using array waveguide (AWG) technology or thin film technology, or a variety of other technologies. Each channel is then optically coupled to separate optical receivers. The optical receiver is typically comprised of a semiconductor photodetector and accompanying electronics.

The total link distance in today's optical transport systems may be two different cities separated by continental distances, from 1000 km to 6000 km, for example. To successfully bridge these distances with sufficient optical signal power relative to noise, the total fiber distance is separated into fiber spans, and the optical signal is periodically amplified using an in-line optical amplifier after each fiber span. Typical fiber span distances between optical amplifiers are 50-100km. Thus, for example, thirty 100 km spans would be used to transmit

optical signals between points 3000 km apart. Examples of in-line optical amplifiers include erbium doped fiber amplifiers (EDFAs), lumped Raman amplifiers and semiconductor optical amplifiers (SOAs).

A duplex optical transport system is one in which voice and data traffic are transmitted and received between parties at opposite ends of the link. There are several architectures that support duplex operation in fiber optical transport systems. Each suffers from limitations.

For example, it is known in the art to use a pair of fiber strands to support duplex operation. One fiber strand of the fiber pair supports traffic flow from a first city to a second city while the second strand of the fiber pair supports traffic flow from a second city to a first city. Each strand is comprised of separate optical amplifiers. At low channel counts, this configuration suffers from a limitation in that the system still demands a large number of optical amplifiers that could potentially be twice the amount needed.

In a conventional two-fiber optical transport system, data is sent from location A to location Z and vice versa using two different fibers. This requires in-line optical amplifiers, dispersion compensation modules (DCMs), dynamic gain equalizers (DGE) and other equipment for each transmission direction.

A conventional single-fiber transport system carries the two directions of data traffic in both directions over the same fiber, using different wavelengths for the two directions. However, the signals from different directions are separated at amplifier sites and amplified by separate amplifiers. Also, dispersion compensation and power equalization are performed separately for each direction. While the transmission capacity of this one-fiber system is reduced by a factor of one half as compared to the two-fiber system, only the required amount of fiber is reduced, while

the amount of transmission equipment stays the same or is even increased due to the required splitting and combining modules.

In a conventional single-fiber system, signals in both traffic directions share one fiber, as opposed to traveling on a fiber pair in a two-fiber system. At the in-line amplifier (ILA) sites, the different traffic directions are typically separated and independently amplified. An additional feature of the single-fiber transport system of this disclosure is the use of a single optical amplifier and DCM for both traffic directions. Additionally, the dynamic gain equalizers (DGEs) can be shared between the traffic directions. This enables cost savings on the equipment side, as the amount of modules (EDFAs, DCMs, DGEs) is virtually reduced by a factor of 2. These cost savings are realized for the first installed channel. In addition, the use of a single fiber provides operational cost savings.

In U.S. Patent Nos. 5,742,416 and 5,812,306 Mizrahi teaches a single fiber bidirectional WDM optical communication system with bi-directional optical amplifiers, where the two traffic directions travel in opposite directions through the optical amplifier. The use of a bi-directional optical amplifier, for example, a bi-directional EDFA to support duplex operation using a single strand of optical fiber potentially saves the cost of one amplifier at each ILA site. A limitation of this prior art implementation is that the bidirectional EDFA may begin to lase in addition to providing amplification. These oscillations and instabilities defeat the goal of data transmission. Keeping the bi-directional EDFA from lasing typically carries additional engineering and financial costs, and ultimately limits the reach and capacity of the transport system. It is desirable to use a single amplifier to support duplex operation without the penalties of a bi-directional EDFA.

In United States Patent No. 5,452,124, Baker teaches a device which uses a four-port wavelength division multiplexing filter and a single erbium doped optical amplifier to implement a dual wavelength bidirectional optical amplifier module. However, the limitation of this prior art implementation is that there is no power balance between incoming and outgoing signals, no provision for optical add/drop multiplexers and no implementation or tuning of dispersion compensation modules.

SUMMARY OF THE INVENTION

In the present invention, a single fiber duplex transmission system is described, in which most of the intermediary components, for examples, optical amplifiers, dispersion compensation modules, and gain equalizers are shared between the transmission directions. This architecture reduces the amount of equipment by half, and therefore implies a reduction of cost and space and power requirements by about 50%. The improvements reduce the number of optical amplifiers in a duplex optical transport system without suffering the penalties present in bi-directional optical amplifiers. The improvements also include a power balance for incoming and outgoing signals of different strengths.

In one aspect of the invention, a multiplexing and de-multiplexing architecture to achieve duplex operation in a single fiber optical transport system through co-directional operation of each optical amplifier is taught.

In another aspect of the invention, an optical add/drop multiplexer architecture to achieve duplex operation in a single fiber optical transport system through co-directional operation of each optical amplifier is taught.

In another aspect of the invention, a module for signal combination and separation in in-line amplifier and optical add/drop multiplexer sites to achieve duplex operation in a single fiber optical transport system through co-directional operation of each optical amplifier is taught.

In another aspect of the invention, a method for power equalization to achieve duplex operation in a single fiber optical transport system through co-directional operation of each optical amplifier is taught.

In another aspect of the invention, a method and strategy for shared dispersion compensation to achieve duplex operation in a single fiber optical transport system through co-directional operation of each optical amplifier is taught.

In another aspect of the invention, a method for full-duplex optical supervisory channel (OSC) over single fiber to achieve duplex operation in a single fiber optical transport system through co-directional operation of each optical amplifier is taught.

In another aspect of the invention, a method of automatically tuning the system operating conditions and power equalization to achieve duplex operation in a single fiber optical transport system through co-directional operation of each optical amplifier is taught.

In another aspect of the invention, a method adding higher capacity to the system to achieve duplex operation in a single fiber optical transport system through co-directional operation of each optical amplifier is taught.

In another aspect of the invention, a simplified add/drop architecture to achieve duplex operation in a single fiber optical transport system through co-directional operation of each optical amplifier is taught.

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the features and advantages of the present invention, reference is now made to the detailed description of the invention along with the accompanying figures in which corresponding numerals in the different figures refer to corresponding parts and in which:

FIG. 1 is a schematic illustration of a full duplex single fiber system in accordance with the invention.

FIG. 2 is a schematic illustration of an inline optical amplifier to support the full duplex single fiber system in accordance with the invention.

FIG. 3(a,b) is a schematic illustration of two alternative optical amplifier implementations using either (a) a single dispersion compensator module for both A-Z and Z-A traffic or (b) separate dispersion compensation modules for A-Z and Z-A traffic to support the full duplex single fiber system in accordance with the invention.

FIG. 4 is a schematic illustration of a full duplex single fiber system that is divided into segments and spans for optical power level and dispersion compensation optimization in accordance with the invention.

DETAILED DESCRIPTION OF THE INVENTION

While the making and using of various embodiments of the present invention are discussed in detail below, it should be appreciated that the present invention provides many applicable inventive concepts that can be embodied in a wide variety of specific contexts. The specific embodiments described herein are merely illustrative of specific ways to make and use the invention and do not delimit the scope of the invention.

In Fig. 1 is shown a block diagram of a full duplex single fiber optical transport system with shared components in accordance with the invention. The single fiber spans **101** connect in-line amplifier (ILA) stations **102**. Together a chain of fiber spans **101** and in-line amplifier stations **102** connect terminal A, **120** and terminal Z, **122**. The notation A and Z is a commonly used notation to indicate different geographic locations. Terminal A transmits optical signal **110** and receives optical signal **111**. Terminal Z transmits optical signal **111** and receives optical signal **110**. Optical signals **110** and **111** propagate in opposite directions, or counter-propagate, in the single fiber spans **101**. In accordance with this invention, optical signals **110** and **111** co-propagate through the in-line amplifiers.

Single fiber spans **101** may be realized by fiber optic strands, wherein the optical fiber is single-mode silica glass fiber such as SMF-28, LEAF or other fiber types. This fiber is typically jacketed and cabled for protection and mechanical ruggedness. In-line amplifier stations **102** will be discussed in more detail below in conjunction with Fig. 2, however, in-line amplifier stations **102** typically comprise optical amplifiers, variable optical attenuators, wavelength selective optical couplers, and may also contain dispersion compensators, dynamic gain equalizers and optical add/drop multiplexers.

Optical signals **110** and **111** are typically comprised optical energy that is encoded with the data or information to be transmitted between geographic locations A and Z. The optical energy is typically generated by semiconductor diode lasers of precise frequencies as specified by the International Telecommunications Union recommendation G.692 (ITU grid). All possible wavelength ranges are contemplated by the invention; however the preferred embodiments specifically include wavelength ranges in the "C" and "L" bands. At terminals **120** and **122**, these different frequencies are multiplexed together before transmission and demultiplexed apart at the receiving terminal. Optical signals **110** and **111** may be wavelength division multiplexed (WDM) signals.

In Fig. 2 is shown a block diagram of a typical in-line amplifier station **102** in accordance with the invention. The in-line amplifier station comprises a functional arrangement of optical components that serves to amplify the optical signals between spans. Shown in Fig. 2 for contextual reference are neighboring fiber spans **101,** which carry optical signal **110** and **111**.

Also shown in Fig 2 are optical couplers **201** and **203**, and optical coupler/decouplers **204** and **206**. In general, optical **201**, **203**, **204**, and **206** referred to as optical couplers and are selected and positioned to enable optical signals **110** and **111** to counter-propagate in fiber spans **101**, and to co-propagate in the optical components comprising in-line amplifier station **102**. In a preferred embodiment, optical couplers **201**, **203**, **204** and **206** are wavelength-selective optical couplers. In a preferred embodiment, the wavelength-selective optical couplers may be realized as a thin film optical coupler. In an alternate preferred embodiment, the wavelength selective optical coupler may be implemented as an inter-leaver, which may be realized as an etalon, or with birefringent crystals, or other inter-leaver technology.

Also shown in Fig. 2 are optical attenuator **210** and optical attenuator **212**. In a preferred embodiment, optical attenuator **210** and **212** are implemented as variable optical attenuators, which may be realized using a number of technologies, including micro-electromechanical machines (MEMS) variable optical attenuators, thermo-optic based variable optical attenuators, traditional mechanical variable optical attenuators, or other variable optical attenuator technology. The use of four separate couplers **201**, **203**, **204** and **206** rather than a single coupler structure to separate and recombine the optical signals between the fiber spans **101** and the optical amplifier stages **220** and **222** is an inventive concept that provides greater optical isolation between the signals **110** and **111** to prevent optical signal degradation effects, and further provides a location for the optical attenuators **210** and **212** to separately adjust the optical power in signals **110** and **111** at the input of the optical amplifier.

Also shown in Fig. 2 is an optical amplifier having stages **220** and **222**. Optical amplifier stages **220** and **222** amplify optical signals **110** and **111** in a co-directional manner in order to compensate for the loss incurred by propagating in the neighboring fiber spans **101**. Optical amplifier stages **220** and **222** may be implemented using erbium doped fiber amplifier (EDFA) technology, semiconductor optical amplifier technology (SOA), discrete Raman amplifier technology or other optical amplifier technology. Optical amplifier stages **220** and **222** may be implemented together in a single stage. As shown in a preferred embodiment, optical amplifier stages **220** and **222** together comprise a two-stage optical amplifier. In the preferred embodiment with the two-stage optical amplifier, a dispersion compensation module **225** may be included between the two stages. The dispersion compensator module adjusts the phase information of the optical pulses in order to compensate for the chromatic dispersion in the optical fiber while appreciating the role of optical nonlinearities in the optical fiber. The

dispersion compensator module may be realized using many dispersion compensation technologies including optical fiber with appropriate dispersion characteristics, higher-order mode fiber-based dispersion compensator technology, optical etalon-based compensators, or other available technologies.

Also shown in Fig. 2 are the optical transmitters **231** and **233** and receivers **230** and **232** of the optical service channel transceivers. In a preferred embodiment, the optical service channel transceivers are 1 gigabit Ethernet (GbE) transceivers with one wavelength propagating in the A-Z direction and another wavelength propagating in the Z-A direction. In the preferred embodiment the optical service channels are outside the wavelength ranges of the data traffic. In one preferred embodiment these ranges are 1550 nm and 1530 nm or 1520 and 1610 respectively.

As shown in Fig. 2, fiber spans **101** are connected to optical couplers **202** and **208**. The function of optical couplers **202** and **208** is to separate the optical service channels from the optical signals **110** and **111** on fiber spans **101**. Also functionally connected to optical couplers **202** and **208** are optical coupler/decouplers **205** and **207**. The function of optical couplers/decouplers **205** and **207** is to separate the two optical service channel wavelengths for the A-Z and Z-A direction onto separate fibers. In a preferred embodiment, the discrimination of this coupling is accomplished by wavelength discrimination, and optical couplers **202**, **208**, **205** and **207** are wavelength-selective optical couplers. The optical couplers **205** and **207** are also coupled to the optical transmitters **231** and **233** and receivers **230** and **232** of the optical service channel transceivers, with each transceiver transmitting and receiving on different wavelengths. In another embodiment, couplers/decouplers **205** and **207** are accomplished by optical circulators.

Optical coupler **202** is also functionally connected to optical coupler **204**. Optical coupler **204** couples incoming traffic from fiber span **101** to optical attenuator **212**, and outgoing traffic from optical coupler **203** to fiber span **101** via optical coupler **202**. In a preferred embodiment the discrimination of this coupling is accomplished by wavelength discrimination and optical couplers **202** and **204** are wavelength-selective optical couplers.

Optical coupler **208** is also functionally connected to optical coupler **206**. Optical coupler **206** couples incoming traffic from fiber span **101** to optical attenuator **210**, and outgoing traffic from optical coupler **203** to fiber span **101** via optical coupler **208**. In a preferred embodiment the discrimination of this coupling is accomplished by spectral discrimination and optical couplers **206** and **208** are wavelength selective optical couplers.

Optical attenuators **210** and **212** are functionally connected to optical coupler **201**. Optical coupler **201** combines the traffic from the A direction with the traffic from the Z direction so that amplification, dispersion compensation and other functions such as dynamic gain equalization are accomplished on the optical signals using the same components in a co-directional, or co-propagating manner. Thus the output of optical coupler **201** is the input to optical amplifier stage **220**. The output of optical amplifier stage **220** is routed to a variable optical attenuator **221**. The output of variable optical attenuator **221** is the input of dispersion compensator **225**. In this preferred embodiment, the output of dispersion compensator **225** is the input of optical amplifier stage **222**. Optical amplifier stage **222**, in this embodiment, acts as the second stage of a two-stage optical amplifier. The variable optical attenuator **221** can be adjusted to control the overall gain of the two-stage optical amplifier. The output of optical amplifier stage **222** is the input to optical coupler **203**. Optical coupler **203** separates the signals that must propagate in the Z-A direction from the optical signals that must propagate in the A-Z

direction. In a preferred embodiment, the discrimination of this coupling is accomplished by spectral discrimination, and optical couplers **202** and **204** are wavelength selective optical couplers.

Since the incoming optical signals **110** and **111** input to optical attenuator **210** and optical attenuator **212** come from spans that may be of different lengths (and therefore have different amounts of attenuation), the incoming optical signals may be at significantly different power levels. The preferred method of correcting for this power variation is to use optical attenuator **210** and optical attenuator **212** to attenuate the higher power signal to the level of the lower power signal. This counterintuitive approach to engineering uneven span lengths provides an optimum equalization scheme. The variable optical attenuators **210** and **212** together with variable optical attenuator **221** within the two-stage optical amplifier comprised of stages **220** and **222** are adjusted to provide the optimal optical power levels at the inputs to fiber spans **101**.

In practice, the attenuation values of variable optical attenuators **210** and **212** should be as small as possible to minimize the impact on system noise accumulation. These separate variable optical attenuators allow the single optical amplifier to be treated as two separate amplifiers. At system startup, beginning at one system endpoint, using endpoint A as an example, the variable optical attenuators at each optical amplifier site in sequence can be optimized to launch the correct optical power level into the outgoing fiber span for the A-Z optical signals by adjusting variable optical attenuators **212** and **221**. When all optical amplifiers have been adjusted for the A-Z optical signals, the optical amplifiers beginning at the Z endpoint can in sequence be tuned for the Z-A optical signals by adjusting variable optical attenuator **210**. If there is a case where variable optical attenuator **210** has been reduced to zero and the attenuation for the Z-A optical signals must still be decreased to achieve the desired output

power at a certain optical amplifier site, the attenuation setting of variable optical attenuator **221** within the optical amplifier can be reduced, increasing the attenuation of variable optical attenuator **212** by an equal amount to maintain the same total attenuation for the A-Z optical signals.

Additional elements may be deployed between optical coupler **201** and optical coupler **203** in a manner that optical signals **110** and **111** share the same element at significant cost and size advantage. Fig. 3(a) illustrates the deployment of a standard in-line amplifier (ILA), with a shared dispersion compensation module **225** as the primary optical element between the optical amplifier stages **220** and **222**. The single fiber system offers two variants of dispersion compensation. The first variant uses a single dispersion compensator **225** at standard ILA site as shown in Fig.3(a).

Separate dispersion compensators **303** and **304** are employed in each direction at sites with dynamic gain equalizers, optical add/drop capability or at other sites where more accurate dispersion compensation is required or where there is a change in fiber type such as SMF to NZDSF. Figure 3(b) illustrates the use of separate dispersion compensators and will be referred to as "ILA-2." As shown in Fig. 3(b), optical attenuator **221** is functionally connected to optical coupler **309**. Optical coupler **308** is functionally connected to dispersion compensator **303** for the A-Z traffic. Optical coupler **308** is also functionally connected to dispersion compensator **304** for the Z-A traffic. Dispersion compensator **303** is functionally connected to optical coupler **309**. Dispersion compensator **304** is also functionally connected to optical coupler **308**. Optical coupler **309** is then functionally connected to optical amplifier stage **222**. A dispersion algorithm, which will be further described later, co-optimizes the dispersion map for both directions. A higher-cost system variant procedure consists of using separate dispersion compensators 303 and

304 for each direction as shown in Fig. 3(b) at all in-line amplifier sites, not just at sites with gain equalization or optical add/drop capability. This approach would allow for an independent optimization of the dispersion map in each direction for improved system performance.

ILA-2 may also have additional optical elements **305** deployed between the optical amplifier **220** and the optical coupler **203**. An additional optical amplifier **306** may be deployed between the additional optical element **305** and the optical coupler **203**. The position of element **305** is for illustrative purposes and does not preclude alternative placement of this element at any point between optical coupler **201** and **203**.

For example, a dynamic gain equalizer may be deployed between optical coupler **201** and optical coupler **203** in order to equalize the power in the individual WDM channels. An optimal placement for this dynamic gain equalizer is shown in Fig. 3(b) as element **305** after the second stage optical amplifier **222** and before optical coupler **203**. The third optical amplifier **306** compensates for the optical attenuation of the dynamic gain equalizer. In a preferred embodiment, the dynamic gain equalizer comprises a liquid crystal dynamic gain equalizer. In another preferred embodiment the dynamic gain equalizer comprises a micro-electro-mechanical machine dynamic gain equalizer. In the most generalized embodiment, the dynamic gain equalizer comprises either a channel-by-channel variable optical attenuator-based gain equalizer or a broadband gain-shape equalizer.

Another example additional optical element **305** is an optical add/drop multiplexer that may be deployed between optical coupler **201** and optical coupler **203** in order to add and drop channels at the in-line amplifier location. An optimal placement for this dynamic gain equalizer is shown in Fig. 3(b) as element **305** after the second stage optical amplifier **222** and before optical coupler **203**. The amplifier **306** compensates for the optical attenuation of the add/drop

multiplexer. It will be apparent to persons skilled in the art that the single-fiber architecture presented here allows the implementation without impairment of the same types of optical add/drop elements traditionally used in dual-fiber systems that are well known in the art and may be based on fixed optical filters or reconfigurable optical filters and switches.

Reference Number	Preferred Embodiment
230 & 231	GBIC, Finisar FTR-1619-7D-55
232 & 233	GBIC, Finisar FTR-1619-7D-53
305	1100 GHz DGE, JDS Uniphase, WBLWX1HL02601
201 & 203	Blue pass filter , Oplink MWDMLB000001111
204 & 206	Red pass filter, Oplink MWDMLR000001111
220 & 306	High Gain EDFA, Onetta IOE 11130L-0002CL
207	CWDM filter (1550 nm), United Optronics CWDVS15500100
205	CWDM filter (1530 nm), United Optronics CWDVS15300100
202 & 208	C-band/L-band Filter, Cierra Photonics CBSPF 1532.681 0164
225, 303 & 304	LEAF DCM, OFS Fitel EHS-963-L
210 & 212	2-ch VOA array , Dicon SCD-5773-A
305	Multiplexer (Blue band), Cierra Photonics MD1001001 0129
305	Multiplexer (Red band), Cierra Photonics MD1001002 0129

The dispersion management for a single-fiber system needs to take into account the propagation quality for both directions for random sets of fiber span lengths. Likewise, installation feasibility and dispersion compensator cost need to be considered.

The accumulated dispersion for the signal at a particular point in the transmission line is the sum of the dispersion values of the passed through fiber spans and dispersion compensation

modules, also referred to as the "dispersion map". In a preferred embodiment, the dispersion map for both A-Z and Z-A directions can be optimized by requiring that the accumulated dispersion values at the input to all segments be approximately 0 ps/nm. With this approach, the accumulated dispersion at the segment endpoints are tightly controlled, while the accumulated dispersion at the intermediate ILA sites can be maintained within a wider acceptable range. This is especially important for terminal and add-drop sites where the individual wavelength channels are connected to equipment outside this system and should be at a known dispersion state.

To facilitate the generation of this optimized dispersion map, the transmission system is divided into segments and spans, as illustrated in Fig. 4, with the endpoints of the segments being either a terminal multiplexer at the system terminal sites or the ILA-2 sites along the system. As different dispersion compensators **303** and **304** may be used for each direction at the ILA-2 sites, the accumulated dispersion can be equalized for all signals at these points. Signals then can be added or dropped if required with the appropriate accumulated dispersion. After dividing the system into segments and spans, the appropriate average accumulated dispersion can be obtained for each segment, also yielding the optimum average accumulated dispersion for the whole system.

In some systems, like that described in U.S. Patent Application No. 10/147,397, incorporated herein by reference, the dispersion compensation modules used to correct for the dispersion of each span are fabricated with discrete values. These discrete values are known as dispersion compensator "granularity." The dispersion compensator granularity, for example, could be equivalent to 10 km of the fiber dispersion. The advantage of this approach is that it allows a finite set of dispersion compensator part numbers to be maintained rather than obtaining modules to precisely match the required values for each fiber span, which can simplify inventory

and reduce cost. The disadvantage is that the set of discrete values of compensation make it unlikely to closely match the required amount of dispersion for a given fiber span. Therefore, in practice, a DCM module is chosen which most nearly approximates the amount of compensation required for a given span.

In all systems certain optical non-linearity's in the fiber need to be accounted for in each span. The non-linearity's are accounted for in the invention by allowing for a predetermined optical amount of uncompensated dispersion. The uncompensated dispersion is referred to as "under-compensation." Under-compensation is a design specification for the system. Typical values for under-compensation in each span range from 0 ps/nm to 100 ps/nm.

A method is described for determining the optimal DCMs and "under-compensation" at each ILA and ILA-2 site considering the granularity of the available DCMs for a single-fiber full-duplex optical transmission system to yield an optimum average accumulated dispersion for the whole system.

Consider a segment with N spans as depicted in Fig. 4. For system installation and dispersion management, the system is divided into segments between either a terminal multiplexer at the system endpoints and a higher-functionality optical amplifier sites (ILA-2s), or between two ILA-2 sites. Consider the dispersion compensation for one segment. Starting for example at one ILA-2 site (referred to as the "A-facing" ILA-2) and working in the A-Z direction, the dispersion compensator 225 at each ILA **102** site in turn is determined according to the preceding fiber span dispersion in the following manner.

The magnitude of the target dispersion compensator value for each span is the dispersion of the previous fiber span minus the specified amount of per-span under-compensation plus a "carry over" value from the previous span. For example, a fiber span that is 100 km in length

consisting of standard single-mode fiber (SSMF) with dispersion of +17 ps/nm-km at 1550 nm, and a system design calling for a 30 ps/nm per-span under-compensation value, the target magnitude of dispersion compensation would be (100km x 17ps/nm-km – 30ps/nm) or 1670 ps/nm. Note that the dispersion of the fiber and the dispersion compensator are by definition opposite in sign, so the target DCM should have a dispersion value of -1670ps/nm.

A DCM is then chosen which most nearly approximates this target value, considering the specified granularity of the available DCM units. Assuming a DCM granularity equal to 10 km of SSMF fiber, the granularity is (10 km x -17 ps/nm) or -170 ps/nm, and the inventory of DCMs would thus consist of modules with dispersion values equal to integer multiples of -170ps/nm. With this granularity and the target dispersion compensation from above of -1670 ps/nm, the closest actual DCM value would be (10 x –170 ps/nm) or –1700 ps/nm. The resulting error between the required dispersion compensation value for a span and the actual value of the available dispersion compensator with finite granularity is defined as the "carry-over" dispersion value. The "carry over" dispersion value is added to the dispersion of the next span to determine the required dispersion compensator 225 at the next ILA site. In this example, the carry-over dispersion value is ((-1670 ps/nm) - (-1700 ps/nm)) equals -30 ps/nm. To be clear, the "per-span under-compensation" value is a system specification designed for optimum optical transmission performance, while the "carry-over dispersion" of each span is a measure of the imperfection of a dispersion map based on DCM units with finite granularity.

Referring again to Figure 4 at the "last ILA" before the "Z-facing" ILA-2 of the segment bordering (the second to last span of the segment) the value of the dispersion compensator is determined in a slightly different way. The dispersion of the following span D_N is added to the dispersion of the preceding span D_{N-1}. Then, the dispersion values of all spans in the segment D_i

are added and divided by the number of spans N. This average dispersion is subtracted from the previously calculated sum, yielding the target dispersion to be compensated as:

$$D_{comp} = D_{N-1} + D_N - \frac{1}{N}\sum_{i=1}^{N} D_i \,, \qquad \text{(Eq. 1)}$$

where D_{comp} is the dispersion value to be compensated, D_i is the dispersion of the i-th fiber span in the segment, and N is the number of fiber spans in the segment. This procedure minimizes the average dispersion error in each segment for both directions of propagation. This dispersion value is then also corrected for the carry-over dispersion from the previous span and the required under-compensation. The carry-over from this site is also calculated differently, as the sum of the dispersion of the previous span plus the value of the chosen dispersion compensator 225 minus the required under-compensation.

At the "Z-facing" ILA-2, the dispersion compensator 303 for the A-Z installation direction is determined based on the dispersion value of the last span before the Z-facing ILA-2 site, the under-compensation specification, and the carry-over value from the previous ILA. The resulting carry-over value is used as an carry-over value for the first ILA of the next segment. Finally, the DCM 304 for the Z-A direction at the "A-facing" ILA-2 site is determined. The sum of all installed ILA dispersion compensators 225 (DCM_i) in the segment is subtracted from the sum of the required dispersion values of all fiber spans of the segment (D_i) including the under-compensation (D_{UC}) to determine the Z-A dispersion compensator 304 for the "A-Facing" ILA-2 of this segment. In this procedure, the resulting carry-over dispersion value from the DCM selection for dispersion compensator 304 is not carried over to another span in equation form:

$$D_{comp} = \sum_{i=1}^{N-1} DCM_i + \sum_{i=1}^{N} (D_i - D_{UC}) \,,$$

where D_{comp} is the dispersion value to be compensated, DCM_i is the value of the ith dispersions compensator, D_i is the dispersion value of the ith span and D_{UC} I sthe specified under-compensation for the span.

In summary, when working in the A-Z direction, this process yields for one segment the dispersion compensator 225 values for all ILA sites, the Z-A dispersion compensator 304 for the beginning ILA-2 of the segment, and the A-Z dispersion compensator 303 for the ending ILA-2 of the segment. This procedure is repeated for all segments of the system.

In an alternative embodiment that provides higher accuracy, the DCM 304 values for all segments can be determined after the other DCM elements of all segments in a system have been determined. In this embodiment, after determining the DCM values in the A-Z direction, the procedure for determining the DCM 304 units begins at the Z Terminal, working back towards the A terminal. The DCM 304 is determined as above, with the addition that the carry-over value from each DCM 304 (D_{CO}) is added to the DCM 304 value at the following ILA-2 site moving in the Z-A direction.

$$D_{comp} = \sum_{i=1}^{N-1} DCM_i + \sum_{i=1}^{N} (D_i - D_{UC}) + D_{CO},$$

While this invention has been described in reference to illustrative embodiments, this description is not intended to be construed in a limiting sense. Various modifications and combinations of the illustrative embodiments, as well as other embodiments of the invention, will be apparent to persons skilled in the art upon reference to the description. It is therefore intended that the appended claims encompass any such modifications or embodiments.